

REPORT DOCUMENTATION PAGE

AD-A233 329

Form Approved
OMB No. 0704-0188

estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. Agency Use Only (Leave blank).		2. Report Date. 1991		3. Report Type and Dates Covered. Journal Article	
4. Title and Subtitle. The Significance of Sediment-Flow Dynamics on Clay Microstructure Development: Riverine and Continental Shelf Environments				5. Funding Numbers. Program Element No. 61153M Project No. 03205 Task No. 330 Accession No. DN257003	
6. Author(s). Huon Li and Richard H. Bennett				8. Performing Organization Report Number. JA 360:028:89	
7. Performing Organization Name(s) and Address(es). Naval Oceanographic and Atmospheric Research Laboratory Ocean Science Directorate Stennis Space Center, MS 39529-5004				10. Sponsoring/Monitoring Agency Report Number. JA 360:028:89	
9. Sponsoring/Monitoring Agency Name(s) and Address(es). Naval Oceanographic and Atmospheric Research Laboratory Ocean Science Directorate Stennis Space Center, MS 39529-5004				11. Supplementary Notes. MFS	
12a. Distribution/Availability Statement. Approved for public release; distribution is unlimited.				12b. Distribution Code. DTIC APR 01 1991 G	
13. Abstract (Maximum 200 words). The highly variable dynamics of coastal and continental shelf waters have a significant effect on the transport and deposition of sedimentary materials. The complex sediment transport mechanisms in continental shelf waters involve the interactions of multiphase flows of solids, liquid, and organics (dissolved and particulate) with multicomponent chemical and minerals species. Also biological processes are pervasive. Fine particles are transported as individual particles and floccules of various sizes and they interact with the fluid flow. The solid particle coagulation, breakup, deposition, erosion, and transport processes and mechanisms depend on the tidal cycles as well as the waves and currents. Particle associations at the sediment water interface are directly related to the particle associations in the suspension, and thus the microstructure at the sea floor is considered to be related to the floc sizes in the water column. The particles (individual particles and flocs) in suspension that are deposited eventually at the depositional interface are the fundamental "building blocks" of the bottom sediment.					
14. Subject Terms. (U) Sediment Transport; (U) Sediments; (U) Pore Pressure; (U) Clay				15. Number of Pages. 10	
				16. Price Code.	
17. Security Classification of Report. Unclassified	18. Security Classification of This Page. Unclassified	19. Security Classification of Abstract. Unclassified	20. Limitation of Abstract. SAR		

Reprinted from

Richard H. Bennett, William R. Bryant, and Matthew H. Hulbert
Editors

Microstructure of Fine-Grained Sediments

© 1991 Springer-Verlag New York, Inc.

Copyright is not claimed for chapters authored by U.S. Government employees (2, 6, 14, 15, 20, 44, 47, 48, 52, 58).
Printed in United States of America.



Springer-Verlag
New York Berlin Heidelberg London
Paris Tokyo Hong Kong Barcelona

CHAPTER 20

The Significance of Sediment-Flow Dynamics on Clay Microstructure Development: Riverine and Continental Shelf Environments

Huon Li and Richard H. Bennett

Introduction

The highly variable dynamics of coastal and continental shelf waters have a significant effect on the transport and deposition of sedimentary materials. The complex sediment transport mechanisms in continental shelf waters involve the interactions of multiphase flows of solids, liquid, and organics (dissolved and particulate) with multicomponent chemical and minerals species. Also biological processes are pervasive. Fine particles are transported as individual particles and floccules of various sizes and they interact with the fluid flow. The solid particle coagulation, breakup, deposition, erosion, and transport processes and mechanisms depend on the tidal cycles as well as the waves and currents. Particle associations at the sediment water interface are directly related to the particle associations in the suspension, and thus the microstructure at the sea floor is considered to be related to the floc sizes in the water column. The particles (individual particles and flocs) in suspension that are deposited eventually at the depositional interface are the fundamental "building blocks" of the bottom sediment.

The objectives of this chapter are to address (1) the significance and role of clay microstructure in flow dynamics (emphasis is on clay microstructure interactions with tide, wave, current, and turbulence), (2) the importance of scale in relation to microstructure and flow dynamics, (3) the role of particle-to-particle interaction, bonding, and shear that occurs near the sediment-water interface, and (4) the role of the "outer region" in sediment transport and microstructure development. Emphasis is on the physicochemical interactions rather than biochemical or biological processes, although these important processes can not be neglected in the final analysis microfabric development. A comprehensive treatment of the field of sediment trans-

port and dynamics is beyond the scope of this chapter and thus limited reference material is discussed.

The surficial sediments are often reworked by organisms (bioturbation) that modify the physical and mechanical properties and microstructure of the sediment (Richardson and Young, 1980; Bennett and Nelsen, 1983). The clay microstructure of continental shelf sediment has been studied extensively by Bowles (1968a, b), Bennett (1976), and Bennett et al. (1977, 1979, 1981). Comprehensive studies of the clay microstructure and the physicochemistry of clays have been presented by Grim (1968), Mitchell (1976), and Bennett and Hulbert (1986). Collective papers on shelf sediment transport can be found in the book edited by Swift et al. (1972) and papers on cohesive sediment dynamics appear in the lecture notes edited by Mehta (1986).

Clay-Water Interactions

Clay Mineral Particles

Clay minerals are crystalline materials that are uniquely layered in plate-like structures. Clay minerals are classified as hydrous aluminum silicates (phyllosilicates). Their structures are commonly composed of composite layers built of components of tetrahedrally and octahedrally coordinated polyhedra. The very common clay minerals are kaolinite, smectite, illite, and mixed-layer clays. The clay mineral particles are usually less than 2 μm . Details of clay mineralogy and classification can be found in works by Grim (1968) and Mitchell (1976). Selected characteristics of the common clay mineral particles are listed in Table 20.1. The shape, size, cation exchange capacity, specific gravity, and specific surface are important properties of the clay minerals

Table 20.1. Characteristics of clay mineral particles.*

Mineral	Shape	Size (μm)	Cation exchange capacity (meq/100 g)	Specific gravity	Specific surface (m^2/g)
Kaolinite	Six-sided flakes	0.1–4 \times 0.05–2	3–15	2.60–2.68	10–20
Montmoril- lonite (Smectite)	Flakes (equi- dimensional)	> 10 \AA \times up to 10	80–150	2.35–2.7	50–120 primary 700–840 secondary
Illites		0.003–0.1 \times up to 10	10–40	2.6–3.0	65–100

*From Mitchell (1976).

that are important in clay microstructure–flow interaction behavior. For example, flocculation and settling velocity are affected by the shape, size, specific gravity, cation exchange capacity, and specific surface of the interacting particles. Atoms of clay minerals are bonded into a three-dimensional structure, and the termination of this structure at a surface produces unbalanced force fields, positive or negative charges depending on the nature of the termination or break (Bennett and Hulbert, 1986). Isomorphous substitution within the crystal lattice also gives the clay particle a net negative charge. When clay mineral particles are 2 μm or less in size, the surface force fields become a significant factor in clay microstructure development. Due to the platy shape of the clay mineral particles and the fact that clay surfaces in general have a residual negative electrostatic charge, surface and colloidal forces exert important influences on particle-to-particle interactions. To preserve electrical neutrality, exchangeable cations are attracted and held on the surfaces and the edges, and in some clays between the unit cells. The quantity of these exchangeable cations necessary to balance the charge deficiency of a particular clay mineral is called the cation exchange capacity (CEC). The CEC is expressed as milliequivalents per 100 g of dry clay (Grim, 1968; Mitchell, 1976).

Suspended Clay Particles – Salt Water System

The behavior of the suspended clay particles in salt water is extremely complex. The flocculation behavior of clays in suspension is dependent on several chemical, physical, and environmental properties such as electrolyte concentration, dielectric constant, temperature, ion size, adsorbed water, pH, and clay mineralogy (Bennett and Hulbert, 1986). The particles may coagulate or remain stable depending on the balance between the electrostatic forces and the van der Waals forces and environmental conditions. The presence of organic matter is an important factor in the aggregation of clay particles. In addition, other complex variables include the bonding of clay particles by mucus

Table 20.2. Characteristics of two mud groups according to Ohtsubo and Muraoka (1986).

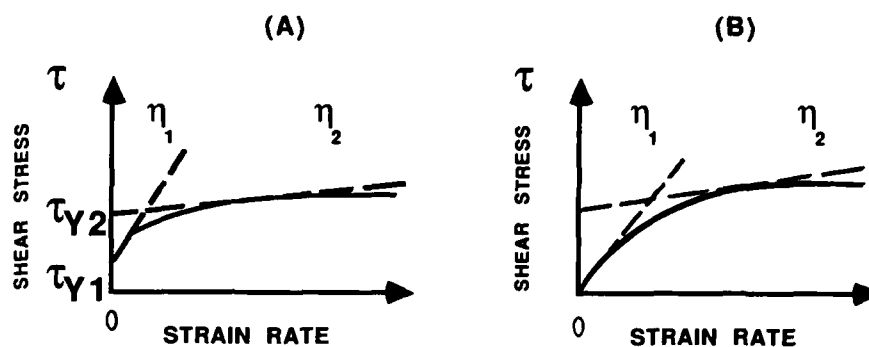
	First mud group	Second mud group
Type of cohesive sediment	Kaolinite Kaolinite + organic matter Montmorillonite Natural muds	Bentonite Bentonite + organic matter
Exchangeable cation	Al^{3+} , Ca^{2+} , H^{+}	Na^{+} , Li^{+}
Resuspension behavior	1. Clear interface between bed surface and upper water 2. Cracks in the bed surface just before bed destruction 3. Bed destruction begins at the cracks 4. No flow of bed at bed destruction	1. Obscure interface between bed surface and upper water 2. Hazy streamwise streak-lines consisting of tiny sediments 3. No cracks in the bed surface for any current condition 4. Flow of bed at bed destruction
Settling type	Collective subsidence	Free settling
Type of flow curve	Type A Existence of τ_{y1} (yield stress) Sharp bend in flow curve	Type B No τ_{y1} (yield stress) Smooth flow curve (power-law type)

*From Ohtsubo and Muraoka (1986).

secretions of algae, bacteria, diatoms, or other members of the benthic and epiflora and fauna common in coastal and oceanic environments (McCave, 1984). Even though neither the physicochemical nor the biochemical bonding forces can be simply predicted or easily measured at the present time, advances have been made in cohesive sediment dynamics in the last 30 years. Major contributions were made by Einstein and Krone (1962), Krone (1962, 1963, 1986), Partheniades (1962, 1965, 1977, 1986), Migniot (1968), McCave (1970, 1984), Mehta (1973, 1986), Owen (1977), and Hunt (1982, 1986).

More recently, Mimura (1989) presented a comprehensive review of cohesive sediment dynamics studies in Japan. Significant experiments on the critical shear stress and rate of resuspension were carried out by Ohtsubo and Muraoka (1986). Forty types of sediment were tested including clays (kaolinite, montmorillonite, and bentonite) and muds taken from different lakes and estuaries. To examine the organic effects, starch and agar were added, respectively, to the clay, and some of the natural muds were tested chemically. The most important result showed that cohesive sediment could be classified into two groups by the difference in the resuspension behavior, settling characteristics, and rheological properties over a wide range of sediment types and water contents. Kaolinite, kaolinite containing organic matter, montmorillonite, and natural muds were classified into one group, namely the first mud group. Bentonite and bentonite containing organic matter were classified as the second mud group. Some important characteristics of the two mud groups are listed in Table 20.2. The two different settling types, collective subsi-

Figure 20.1. Shear stress-strain rate relationship for two mud groups (A) Type A has a yield stress; (B) Type B has no well-defined yield strength. (From Ohtsubo and Muraoka, 1986.)



dence and free settling, indicate the difference in cohesive forces between the two mud groups. In the first mud group, collective subsidence settling occurs as the suspended particles aggregate and form a particular chain-like structure. The different types of relationship between shear stress and strain rate were obtained as shown in Figure 20.1. Type A curve, which has a yield stress τ_{y1} and a sharp bend indicative of material having a finite shear strength, was obtained for the first mud group. Type B curve, which has no well-defined yield strength, was representative of the second mud group. The existence of the yield stress τ_{y1} suggests that the first mud group has strong bonding and/or structure between particles.

The sizes of hydrated ions are expected to play an important role in the aggregation of suspended particles. Some of the important possible mechanisms for clay-saltwater interactions include (1) adsorbed hydrated cations which form the diffuse double layer, (2) hydrogen bonding, (3) hydration of exchangeable cations, (4) charged surface-dipole attraction, (5) attraction by van der Waals forces, (6) electroosmosis, (7) chemicoosmosis, (8) thermal diffusion, (9) external body forces, and (10) hydrodynamic forces.

Flow Dynamics

Water Mass Dynamics on the Continental Shelf

The transport of sediment in the water column and as bed load material is strongly influenced by both the fluid motion as well as the microstructure in suspension. The dynamics and micro-scale characteristics of the water masses also significantly affect the developmental history of fine-particle microstructure. On the continental shelf, a wide range of spatial and temporal scales of water motion exists. Since long-term changes involve deposition and low rate transport of clay materials, water motion of low intensity is important over geological time scales. Wave-induced water motion and currents, tidal-generated currents, and currents induced by fluid density differences are important for sediment transport under certain environmental conditions. A brief discussion of the various aspects of fluid flow important in sedi-

ment transport studies was presented by Weggel (1972) and a review of the coastal processes was given by Johnson and Eagleson (1966). According to Johnson and Eagleson, ocean currents can be classified into several groups: (1) currents generated by density distributions in the sea, (2) currents resulting from wind stresses, (3) tidal currents and those associated with internal waves, (4) currents caused by the activity of surface waves, and (5) currents induced by the intrusion of freshwater entering the ocean at river mouths. The various types of currents are depicted in Figure 20.2.

The flow regions in a vertical section of continental shelf water are shown schematically in Figure 20.3. The flow characteristics for the "wall" region are very significant in sediment transport and the dynamics are different from the main water mass body. The turbulence and dynamics of the "wall" region are of most importance in terms of sediment transport and suspended sediment microstructure.

Turbulence

Turbulence is the irregular motion of rotational flows. The thermodynamic and hydrodynamic variables of these flows depict the chaotic fluctuations in space and time coordinates. The following possible mechanisms of turbulence generation in the ocean were pointed out by Monnin and Ozmidov (1985):

1. Instability of vertical velocity gradients in drift flow—these velocity gradients are induced by direct effects of the wind on the upper mixed layer (UML).
2. Overturning of surface waves—this mechanism, and to a less extent the hydrodynamic instability of wave motions induced by surface waves, is the most powerful source of UML turbulence.
3. Instability of vertical velocity gradients in stratified large-scale oceanic flows—because of the large scale and low rate of turbulent energy generation, this mechanism is considered not important for shelf sediment transport.
4. Hydrodynamic instability of quasihorizontal mesoscale non-stationary flows—empirical evidence exists for the generation of small-scale turbulence.

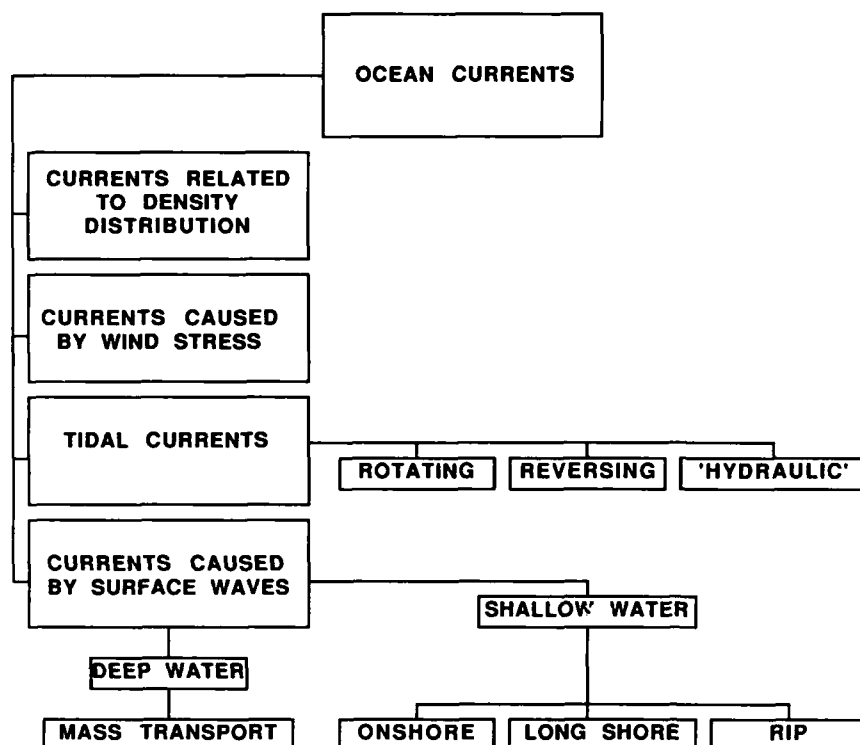


Figure 20.2. Classification of ocean currents. (From Johnson and Eagleson, 1966.)

5. Instability of local velocity gradients in internal waves—the instability of internal waves in the turbulent microstructure of the water increases the turbulent energy by a very small amount, which results in only slight dissipation.
6. Convection in layers with unstable density stratification—this mechanism can create turbulent (microstructure) layers.

7. Instability of vertical velocity gradients in the bottom boundary layer (BBL)—this type of turbulence is created by Ekman layer instability.

In addition to the turbulence generation mechanisms listed above, the dynamics and turbulence characteristics in the “wall” region are important considerations in continental shelf water dynamics. The thickness of the “wall” region (Nychas et al., 1973) is defined by

$$\delta_w = 70\nu/u_* \quad (1)$$

where u_* ($u_* = \tau_b^{1/2}\rho^{-1/2}$, here τ_b is the bed shear stress and ρ is the density of the water) is the friction velocity at the wall, and ν is the kinematic viscosity of the water. Turbulence in the “wall” region is *not isotropic and not homogeneous*. The turbulence, however, is termed isotropic if its statistical properties have no preferential direction, and it is said to be homogeneous if a random motion exists whose average properties are independent of position in the fluid. Classical works of turbulence were presented by Hinze (1959), Batchelor (1960), and Townsend (1976).

Dynamics in the “Wall” Region

A thin viscous sublayer exists next to the interface in the “wall” region for a smooth, rigid boundary. The ranges of the viscous sublayer and the “wall” region can be estimated as follows:

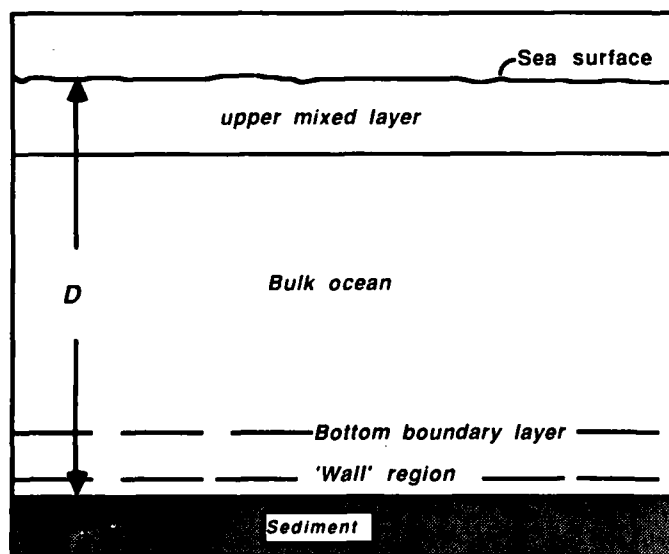


Figure 20.3. Flow regions in a vertical section (not to scale).

Table 20.3. Estimated thickness ranges for viscous sublayer and "wall" region.

	Friction velocity u_* (cm/sec)		
	0.1	1.0	10
Viscous sublayer (cm)	<0.5	<0.05	<0.005
"Wall" region (cm)	<7.0	<0.7	<0.07

$$\text{Viscous sublayer} \quad y < 5\nu/u_* \quad (2)$$

$$\text{"Wall" region} \quad y < 70\nu/u_* \quad (3)$$

where u_* is the friction velocity and ν is the kinematic viscosity of the water. Assuming $\nu = 0.01 \text{ cm}^2/\text{sec}$, the thickness ranges are estimated in Table 20.3. The condition for a boundary to be hydraulically smooth is that the dimensionless roughness Reynolds number

$$u_* k / \nu < 5 \quad (4)$$

where k is the roughness parameter (Schlichting, 1960). According to Einstein (1950), the total friction velocity (or shear stress) can be expressed as

$$u_{*t} = u_* + u_{*i} \quad (5)$$

where u_* is the "pure friction" component interacting between the fluid and the bed surface, irrespective of whether the surface is a flat plane or irregular, and u_{*i} is the resultant of the drag forces acting on the irregularities. Discussions of the bottom friction were given by Yalin (1977). Based on Einstein's suggestion as stated in Eq. (5), the sea bottom is likely to be classified as smooth. Even for the rough boundary ($5 < u_* k / \nu < 70$, where k is the grain roughness parameter), the concept of the "wall" region is still valid.

The high shear and the dynamics of the viscous sublayer and the "wall" region are the key mechanisms that play a role in the deposition, resuspension, and floc breakup. From turbulent structure measurements in flat plate and pipe flow, the regions of maximum production and maximum dissipation are just outside the viscous sublayer (Hinze, 1959; Townsend, 1976). It is important to note that a dynamic viscous sublayer model was proposed by Einstein and Li (1955, 1956, 1958). The proposed model predicts a periodic growth and decay of the viscous sublayer. As a consequence of this model some estimates can be made for the generation of turbulence near the boundary. The unsteady and intermittent model was based on visual observations, pressure fluctuation measurements, and logic. Observations revealed that dye and sediment particles were exchanged between a smooth boundary and the turbulent flow through the viscous sublayer, thus making the assumption of a quasisteady sublayer impossible (Einstein and Li, 1958). Additional visual and quantitative studies of the viscous sublayer and "wall" region were carried out by Kline et al. (1967). An experimental investigation with hot-wire anemometers was performed by Gupta et al. (1971) to evaluate the spatial structure

in and near the viscous sublayer. Later experiments (Nychas et al., 1973; Offen and Kline, 1975) confirmed that the production of the Reynolds stress is intermittent and is associated with a sequence of motions called "bursting" (Offen and Kline, 1974, 1975; Dyer, 1986).

Wave Boundary Layer

In continental shelf waters, the wave action may reach the sea bottom. It is well known that the irrotational theory can be applied to the entire gravitational wave motion except for a very thin layer adjacent to solid boundaries. Near solid boundaries the viscous effect cannot be neglected as compared with the inertia forces, and the thin layer can be treated according to the boundary layer theory. An experimental study was carried out by Li (1954) to investigate the wave boundary stability by oscillating a plate in still water with the range, amplitude, and period as computed by wave theory. According to Li (1954), the thickness of the oscillatory boundary layer is defined as

$$\delta_i = 6.5 \sqrt{\nu/\omega} \quad (6)$$

where ν is the kinematic viscosity and ω is the angular frequency. The thickness of the oscillatory boundary layer is very thin. For an oscillatory period of 10 sec, δ_i has the thickness about 0.82 cm.

The critical Reynolds number at which the transition from laminar to turbulent takes place is found to be a constant

$$R = \omega^{1/2} d_i / \nu^{1/2} = 800 \quad (7)$$

where d_i is the maximum amplitude of horizontal displacement at the boundary. The critical Reynolds number should be lower in the field (*in situ*) than the laboratory values stated above since the flow disturbances are much higher in the field.

Further information for wave boundary layers and their relation to sediment transport was provided by Teleki (1972) and Einstein (1972). Laboratory experiments were carried out by Kemp and Simons (1982) to investigate the interaction between waves and currents. Theoretical models were presented by Smith (1977), Grant and Madsen (1979), Grant et al. (1984), Herbich et al. (1984), and Shen (1986).

Detrital Particles and Flow Interactions

Fluid-Particle Dynamics

The transport of solid particles by random fluid motions that may include molecular motion and turbulence is diffusive in nature. For cohesive particles, the particle-particle interaction and the change of particle sizes make the problem very complex. Several scales of interaction are involved in the particle and flow dynamics: molecular scale, solid particle size, turbulent eddy

Table 20.4. Densities and shear strengths of aggregates in the capillary viscometer.*

Sample	Density (g/cm ³)	Shear strength (dyn/cm ²)	Cation exchangeable capacity [†] (meq/100 g)
Wilmington District	1.250	21.0	32
Brunswick Harbor	1.164	33.7	38
Gulfport Channel	1.205	45.9	49
San Francisco Bay	1.269	21.8	34
Delaware River	1.305	11	23
Potomac River	1.437	19	15
White River	1.212	48.6	60

*From Krone (1986).

[†] Cation exchange capacity of the < 10 µm fraction.

size, and magnitude of the mean motion. Because of the random nature of sediment-fluid dynamics and the lack of complete understanding of the problems and microscale events, both statistical and semiempirical approaches are required to approach a solution to the sediment transport processes.

For clay particles to aggregate, mechanisms must exist to bring particles into collisions and the collisions must result in flocculation (coagulation). The flocculation process is due to the physicochemical interaction of the clay surfaces and surrounding electrolytic fluid. Common physical mechanisms involving particle collisions are Brownian motion, laminar and turbulent shear, and differential settling (see Bennett et al., this volume). A general equation for the particles undergoing flocculation including their size distribution was given by Friedlander (1977). The "coagulation kernels" were found for the Brownian motion, laminar shear, turbulent shear, and differential settling. Analogous to the work in the universal equilibrium concept of turbulence, a similar solution for coagulation was developed by Friedlander (1960) and later extended by Hunt (1982). Similar to flocculation, the equation for the particle size distribution undergoing breakup was given by Jeffrey (1982); however, the "breakup kernels" were not found. Additional data on the coagulation and breakup were presented by McCave (1984) and Hunt (1986). Based on known measurements, the size distribution can be estimated for shelf environments when the system is free of biological influences: (1) particle sized spectra are flat at low concentrations ($< 1 \times 10^{-5}$ g/cm³) in the size range 1–60 µm (Eisma and Kalf, 1979), and (2) at moderate concentration ($\sim 1 \times 10^{-4}$ g/cm³), a modal peak occurs between 5 and 20 µm (Kranck, 1973, 1981). Several modal peaks, however, may exist in the shelf where plankton are important. Once the size of the floc is known, the settling velocity of a single floc can be estimated theoretically or empirically.

Krone (1986) presented an hypothesis that described the orders of aggregates and laboratory measurement results of the capillary viscometer for density, shear strengths of aggregates, and cation exchange capacity (Table 20.4). The Bingham shear strength correlates with the cation exchange capacity as

$$\tau_B = 3.92 + 0.8447 (\text{CEC}) \quad (8)$$

Table 20.5. Properties of sediment aggregates.*

Sediment sample	Order of aggregation	Density [†] (g/cm ³)	Shear strength (dyn/cm ²)	Porosity [‡] (n)
Wilmington District	0	1.250	21	0.862
	1	1.132	9.4	0.934
	2	1.093	2.6	0.958
Brunswick Harbor	3	1.074	1.2	0.970
	0	1.164	34	0.914
	1	1.090	4.1	0.960
Gulfport Channel	2	1.067	1.2	0.974
	3	1.056	0.62	0.981
	0	1.205	46	0.889
San Francisco Bay	1	1.106	6.9	0.950
	2	1.078	4.7	0.967
	3	1.065	1.8	0.975
White River (in salt water)	0	1.269	22	0.850
	1	1.179	3.9	0.905
	2	1.137	1.4	0.931
	3	1.113	1.4	0.966
	4	1.098	0.82	0.955
	5	1.087	0.36	0.962
	6	1.079	0.20	0.967
	0	1.212	49	0.885
	1	1.109	6.8	0.948
	2	1.079	4.7	0.967
	3	1.065	1.9	0.975

*From Krone (1986).

[†] Density in sea water = 1.025 g/cm³.[‡] Solid particle density = 2.65 g/cm³.

In Table 20.5, the results of the rotating cylinder viscometer are shown for the order of aggregation, density, and shear strength, as well as the porosity. Krone stated that

1. The order of the suspended aggregates depends on the history of the suspension: such as if the particles have been suspended in fluid zones having very high velocity gradients or if they are newly formed from dispersed mineral particles, the order would be zero. Aggregates that have formed in moderate velocity gradients were classified as one order higher.
2. Settling aggregates that adhere to the bed surface during deposition have a structure that at the bed surface is classified as one order higher than that of the depositing aggregate. The critical shear stress for deposition (τ_{cd}) also is considered one order of aggregation higher than the order of the depositing aggregate.

Flume studies of deposition of suspended cohesive sediment (Krone, 1986) showed that

$$dc/dt = -(W_s c/h) (1 - \tau_b/\tau_{cd}) \quad (9)$$

where c is the concentration, t is the time, W_s is the settling velocity, h is the water depth, τ_b is the bed shear stress, and τ_{cd} is the critical shear stress for deposition. The term $(1 - \tau_b/\tau_{cd})$ expresses the probability of the settling aggregates to adhere to the bed.

Table 20.6. Values of τ_{cd} for three sediments.*

Sediment	τ_{cd} (dyn/cm ²)
Kaolinite	1.5
Bay mud	1.0
Maracaibo mud	0.8

*From Mehta (1986).

Mehta (1973, 1986) carried out extensive deposition tests under steady flows and reanalyzed some previous flume data. He found that the critical shear stress τ_{cd} depended on the sediment composition, and varied from 0.4 to 1.5 dyn/cm². The values of τ_{cd} are shown in Table 20.6 for three sediments.

Partheniades (1962, 1965, 1986) conducted experimental and theoretical studies for both erosion and deposition. The first experiments were conducted on a remolded bed at a comparable field density and of uniform consistency about 1 in. thick. At constant bed shear stresses above a threshold value, $\tau_{ce} = 0.96$ dyn/cm², the rates of erosion were constant and independent of the suspended sediment concentration (Partheniades, 1962, 1965, 1986). Data and observations indicated that no simultaneous erosion and deposition of sediment occurred during the experiments. Based on statistical considerations, models were developed by Partheniades for erosion, deposition, and sediment-flow interactions. The stochastic model for sediment-flow interaction was based on an extension of the Einstein (1950) approach for the bed-load function. The model indicates that simultaneous erosion and deposition of sediment particles may occur only in a limited range for cohesive sediments. Laboratory studies of erosion and deposition are very useful for studying and describing shelf sediment transport processes and clay microstructure development.

Turbulent Scale, Dissipation Rate, and Mean Shear Rate

Let us now address the subject concerning the scale of turbulence. For isotropic turbulence, Kolmogoroff made the following hypothesis (Hinze, 1959): "At sufficiently high Reynolds numbers there is a range of high wave-numbers where the turbulence is statistically in equilibrium and uniquely determined by the parameters ϵ and ν . This state of equilibrium is universal" (Hinze, 1959, p. 184). ϵ and ν describe the rate of turbulent energy dissipation and the molecular kinematic viscosity, respectively.

From dimensional reasoning, the characteristic scales can be obtained from the equilibrium range as

$$\text{Length scale: } \eta = (\nu^3/\epsilon)^{1/4} \quad (10)$$

$$\text{Velocity scale: } \nu = (\nu\epsilon)^{1/4} \quad (11)$$

$$\text{Shear rate scale: } G = (\epsilon/\nu)^{1/2} \quad (12)$$

The rate of turbulent energy dissipation (or production), ϵ , in the ocean was estimated by Monin and Ozmidov (1985) as (1) in

Table 20.7. Characteristic scales in equilibrium range for three layers of the ocean.

Region	Dissipation rate $\epsilon = (\text{cm}^2/\text{sec}^3)$	Length scale η (cm)	Velocity scale ν (cm/sec)	Shear rate scale G (sec ⁻¹)
Upper mixed layer	$10^{-2} - 10^{-1}$	$10^{-1} - 0.56 \times 10^{-1}$	$10^{-1} - 1.8 \times 10^{-1}$	1-3.2
Bulk ocean	10^{-5}	5.6×10^{-1}	1.8×10^{-2}	3.2×10^{-2}
Bottom boundary layer	10^{-4}	3.2×10^{-1}	3.2×10^{-2}	10^{-1}

upper mixed layer, $\epsilon \approx 10^{-2} - 10^{-1}$ cm²/sec³; (2) in bulk ocean, $\epsilon \approx 10^{-5}$ cm²/sec³; and (3) in BBL, with turbulence created chiefly by Ekman layer instability, $\epsilon \approx 10^{-4}$ cm²/sec³. Based on these estimates, the characteristic scales were determined (Table 20.7). It is important to note that the assumption of local isotropy and equilibrium range is reasonable in all the three layers except in the "wall" region. In the "wall" region, the rate of energy dissipation and the mean shear rate are estimated based on the following relationships:

In the viscous sublayer, the viscous dissipation rate is

$$\epsilon_v = u_*^4/\nu \quad (13)$$

and mean shear rate is

$$du/dy = u_*^2/\nu \quad (14)$$

At the edge of the "wall" region the turbulent dissipation rate is

$$\epsilon = u_*^3/\kappa y \quad (15)$$

and mean shear rate is

$$du/dy = u_*/\kappa y \quad (16)$$

where κ is the von Karman's constant and has the value of 0.4 for clean fluids (may be lower with sediment).

The estimates of flow characteristics are given in Tables 20.8 and 20.9 for the viscous sublayer and for the edge of the "wall" region. When the friction velocity reaches the value of 1.0 cm/sec, high viscosity dissipation and high mean shear rates occur in the viscous sublayer (Table 20.8) and the turbulent dissipation rates at the edge of the "wall" region (Table 20.9) are higher than that of the dissipation rate in the upper mixed layer.

Table 20.8. Estimate of flow characteristics in the viscous sublayer.

	Friction velocity u_* (cm/sec)		
	0.1	1.0	10
Viscous dissipation rate ϵ_v (cm ² /sec ³)	10^{-2}	10^2	10^6
Mean shear rate du/dy (sec ⁻¹)	1	10^2	10^4

Table 20.9. Estimate of flow characteristics at the edge of "wall" region.

	Friction velocity u_* (cm/sec)		
	0.1	1.0	10
At $y = 70 u/u_*$			
Turbulent dissipation rate ϵ (cm^2/sec^3)	3.6×10^{-4}	3.6	3.6×10^4
Mean shear rate $\frac{du}{dy}$ (sec^{-1})	3.6×10^{-2}	3.6	3.6×10^2

bulk ocean, and bottom boundary layer. Due to the fact that the turbulent dissipation rate and the turbulent production rate are much higher inside the "wall" region than outside, and because of the unsteady, intermittent, dynamic nature of this region, *the breakup of flocs takes place mainly in the "wall" region*. On the other hand, the flocs also may affect the turbulent characteristics, and the structure of the "wall" region, the fluid and solids interacting synergistically. The turbulence in the other layers contributes to the mixing, flocculation, diffusion, and deformation of the flocs, but at generally lower dynamic energies than in the "wall" region.

Description of the Particles and Flow Interactions on the Shelf and Riverine Environments: Significance to Clay Microstructure

Despite the complexity of the particle types and morphology and flow dynamics on the continental shelf, the mechanics of solid particle or floc movement can be described and approximated as follows:

1. The motion of any solid particle (or aggregate) is determined by Newton's laws. The forces acting on the particle include hydrodynamic forces, electrochemical particle-particle interaction forces, and gravitational force. Due to the various shapes of particles and the random nature of the force actions, the particle may reorientate and floccules may deform.
2. As an example, suppose we follow a solid particle (aggregate) in a location outside the "wall" region (i.e., $yu_*/v > 70$). Before a particle-particle collision, the motion of this particle can be considered as a single particle that is subjected to the actions of the steady current, periodic motions such as wave and tide, flow turbulence, Brownian motion, and gravitational force. This particle reorientates or moves more or less in a random manner. However, the motion of the particle has the tendency to follow a downward trajectory due to the gravitational force. Once particle-to-particle collision occurs, the compound particle may either bond or separate depending on the impact force and the physicochemical forces. The strength of the newly formed aggregate is probably dependent on (a) the number of molecular bonds at the

particle-particle contact, (b) the type of available hydrated ions in the double layer, (c) the presence or absence of other molecules (organic and inorganic) in proximity to the points of contact, and (d) the geometry of the contact area and relative orientation of the particles [edge-to-edge (E-E) and edge-to-face (E-F) contact generally would be weaker than face-to-face (F-F) contacts]. After the particle-particle collision, the new aggregate will be considered as a single particle as before and the processes will continue in the flow regime outside the "wall" region.

3. As the aggregate drops inside the "wall" region and into the viscous sublayer, the particle may deform, break up, and eject outside the region due to the high shear and dynamics of this region. Because of the unsteady and intermittent nature in the "wall" region, the high lift force may prevent aggregate deposition. However, the aggregate may pass through the "wall" region and be deposited at the interface if the bottom friction velocity is below a critical value ($u_{*cd} \approx 0.6-1.3$ cm/sec). Simultaneous erosion and deposition generally do not occur. The deposited sediment will consolidate, be reworked, and be altered by the mechanical, chemical, and biological forces and mechanisms driving microfabric development (Bennett et al., this volume). As the bottom friction velocity reaches another critical value ($u_{*ce} \approx 0.6-3.0$ cm/sec) at another time, the deposited sediment will be resuspended.
4. Since the nature of the problem has virtually infinite degrees of freedom, the high variability in time, space, and scale, both a statistical concept and semiempirical approaches are required to develop meaningful predictive models of sediment transport and deposition and the processes and mechanisms in microfabric development.

Based on this study and the above descriptions and the discussions in previous sections, the suspended clay microstructure, can be described as follows: (1) clay mineral particle microstructure (fabric and physicochemistry) are the fundamental "building blocks"; (2) the available particle size distribution affects the aggregate size distribution, which commonly is flat in the range 1–50 μm (where plankton are important several modes can exist); (3) the density of the aggregates have the range 1.06–1.4 g/cm^3 ; (4) after the initial contact, which is dominantly edge-to-face in the marine environment, staircase structure (stronger and more stable structure) is preferred due to the high shear in the viscous sublayer and the "wall" region; and (5) chain-like and vortex-like structures may exist partially due to turbulence especially in the "wall" region.

Summary and Conclusions

The suspended clay particles in salt water may coagulate due to the effects of electrostatic forces, van der Waals forces, and biochemical activities. The flocculation-deflocculation behavior of

clays in suspension is dependent on many physicochemical properties, especially the clay mineral types, their particle size distribution, and the ionic characteristics of the fluid. The particles and flow interactions such as Brownian motion, laminar and turbulent shear, and differential settling are of importance in the flocculation behavior.

A thin water layer near the bottom plays a very important role on the suspended clay particle and aggregates and on the particles at the depositional interface. This thin layer is called a "wall" region and has a thickness equal to $70\nu/u_*$, where ν is the kinematic viscosity of the fluid and u_* is the "pure" friction velocity. Outside the "wall" region, the turbulence and the mean shear play a role in flocculation. Inside the "wall" region, the particle aggregate may break up and be ejected outside the region due to the high shear and dynamics of the "wall" region and the microfabric of the floccules may be changed. The aggregate may pass through the "wall" region and be deposited on the bottom if the friction velocity is below a critical value (e.g., $u_{*cd} \approx 0.6\text{--}1.3$ cm/sec).

The friction velocity due to the drag forces acting on the irregularities, u_{*i} , is a contribution mainly outside the "wall" region insofar as the particle-flow interaction is concerned. Due to the distinct roles of the u_* and u_{*i} , the application of the logarithmic law is not sufficient for the determination of the friction velocity and the roughness length.

The interaction of waves and currents is complex. For the friction velocity, a linear superposition is recommended as the first approximation.

References

- Batchelor, G.K., 1960. *The Theory of Homogeneous Turbulence*. Cambridge University Press, London, 197 p.
- Bennett, R.H., 1976. Clay fabric and geotechnical properties of selected submarine sediment cores from the Mississippi Delta. Ph.D. dissertation, Texas A&M University, College Station, TX, 269 p.
- Bennett, R.H., and M.H. Hulbert, 1986. Clay Microstructure. International Human Resources Development Corporation, Boston, MA, 161 p.
- Bennett, R.H., and T.A. Nelsen, 1983. Seafloor characteristics and dynamics affecting geotechnical properties at shelfbreaks. In: Stanley, D.J., and G.T. Moors (eds.), *The Shelfbreak: Critical Interface on Continental Margins*. Tulsa, OK, SEPM, 467 p.
- Bennett, R.H., W.R. Bryant, and G.H. Keller, 1977. Clay fabric and geotechnical properties of selected submarine sediment cores from the Mississippi Delta. NOAA Professional Paper 9, U.S. Department of Commerce, 86 p.
- Bennett, R.H., W.R. Bryant, and G.H. Keller, 1979. Clay fabric and related pore geometry of selected submarine sediments: Mississippi Delta. *Scanning Electron Microscopy I*, p. 519-524 and p. 424 (discussion).
- Bennett, R.H., W.R. Bryant, and G.H. Keller, 1981. Clay fabric of selected submarine sediments: fundamental properties and models. *Journal of Sedimentary Petrology*, v. 51(1), p. 217-232.
- Bowles, F.A., 1968a. Electron microscopy investigation of the microstructure in sediment samples from the Gulf of Mexico. Ph.D. dissertation, Texas A&M University, College Station, TX, 140 p.
- Bowles, F.A., 1968b. Microstructure of sediments: investigation with ultrathin section. *Science*, v. 159, p. 1236-1237.
- Dyer, K.R., 1986. *Coastal and Estuarine Sediment Dynamics*. Wiley, New York, 342 p.
- Einstein, H.A., 1950. The bed-load function for sediment transportation in open channel flow. Technical Bulletin No. 1026, U.S. Department of Agriculture, Washington, D.C., 71 p.
- Einstein, H.A., 1972. The basic description of sediment transport on beach. In: Meyer, R.E. (ed.), *Waves on Beaches and Resulting Sediment Transport*. Academic Press, New York, 462 p.
- Einstein, H.A., and R.B. Krone, 1962. Experiments to determine modes of cohesive sediment transport in salt water. *Journal of Geophysical Research*, v. 67, p. 1451-1461.
- Einstein, H.A., and H. Li, 1955. Shear transmission from a turbulent flow to its viscous boundary sub-layer. 1955 Heat Transfer and Fluid Mechanics Institute, UCLA, paper no. XIII, 16 p.
- Einstein, H.A., and H. Li, 1956. The viscous sublayer along a smooth boundary. *Journal of Engineering Mechanics Division, Proceedings, American Society of Civil Engineers*, paper no. 945, 27 p.
- Einstein, H.A., and H. Li, 1958. The viscous sublayer along a smooth boundary. *Transactions of the American Society of Civil Engineers*, v. 123, p. 293-313.
- Eisma, D., and J. Kalf, 1979. Distribution of particle size of suspended matter in the southern bight of the North Sea and the Eastern Channel. *Northerlands Journal for Sea Research*, v. 13, p. 298-324.
- Friedlander, S.M., 1960. On the particle-size spectrum of atmospheric aerosols. *Journal of Meteorology*, v. 17, p. 373-374.
- Friedlander, S.M., 1977. *Smoke, Dust and Haze: Fundamentals of Aerosol Behavior*. Wiley, New York, 317 p.
- Grant, W.D., and O.S. Madsen, 1979. Combined wave and current interaction with a rough bottom. *Journal of Geophysical Research*, v. 84, p. 1797-1808.
- Grant, W.D., A.J. Williams III, and S.M. Glenn, 1984. Bottom stress estimates and their prediction on the northern California continental shelf during CODE-1: the importance of wave-current interaction. *Journal of Physical Oceanography*, v. 14, p. 506-527.
- Grim, R.E., 1968. *Clay Mineralogy*, 2nd ed. McGraw-Hill, New York, 596 p.
- Gupta, A.K., J. Laufer, and R.E. Kaplan, 1971. Spatial structure in the viscous sublayer. *Journal of Fluid Mechanics*, v. 50, p. 493-512.
- Herbich, J.G., R.E. Schiller, R.K. Watanage, and W.A. Dunlap, 1984. *Seafloor Scour*. Marcel Dekker, New York, 320 p.
- Hinze, J.O., 1959. *Turbulence*. McGraw-Hill, New York, 586 p.
- Hunt, J.R., 1982. Self-similar particle-size distributions during coagulation: theory and experimental verification. *Journal of Fluid Mechanics*, v. 122, p. 169-185.
- Hunt, J.R., 1986. Particle aggregate breakup by fluid shear. In: Mehta, A. J. (ed.), *Estuarine Cohesive Sediment Dynamics. Lecture Notes on Coastal and Estuarine Studies 14*. Springer-Verlag, New York, 473 p.
- Jeffrey, D.J., 1982. Aggregation and breakup of clay flocs in turbulent flow. *Advances in Colloid and Interface Science*, v. 17, p. 197-211.
- Johnson, J.W., and P.S. Eagleson, 1966. Coastal processes. In: Ippen, A.T. (ed.), *Estuary and Coastline Hydrodynamics*. McGraw-Hill, New York, 744 p.
- Kemp, P.H., and R.R. Simmons, 1982. The interaction between waves and turbulent current: waves propagating with the current. *Journal of Fluid Mechanics*, v. 116, p. 227-250.
- Kline, S.J., W.C. Reynolds, F.A. Scharub, and P.W. Runstadler, 1967. The structure of turbulent boundary layers. *Journal Fluid Mechanics*, v. 30, p. 741-776.
- Kranck, K., 1973. Flocculation of suspended sediment in the sea. *Nature*, v. 246, p. 348-350.
- Kranck, K., 1981. Particulate matter grain size characteristics and flocculation in a partially mixed estuary. *Sedimentology*, v. 28, p. 107-114.
- Krone, R.B., 1962. Flume studies of the transport of sediment in estuarial shoaling processes. *Hydraulic Engineering Laboratory and Sanitary Engineering Laboratory, University of California, Berkeley*, 110 p.

- Krone, R.B., 1963. A study of rheologic properties of estuarial sediments. Hydraulic Engineering Laboratory and Sanitary Engineering Laboratory, University of California, Berkeley, 91 p.
- Krone, R.B., 1986. The significance of aggregate properties to transport processes. In: Mehta, A.J. (ed.), *Estuarine Cohesive Sediment Dynamics. Lecture Notes on Coastal and Estuarine Studies 14*. Springer-Verlag, New York, 473 p.
- Li, H., 1954. Stability of oscillatory laminar flow along a wall. U.S. Army Corps of Engineers Technical Memorandum no. 47, 48 p.
- McCave, I.N., 1970. Deposition of fine-grained suspended sediment from tidal current. *Journal of Geophysical Research*, v. 75, p. 4151-4159.
- McCave, I.N., 1984. Erosion, transport and deposition of fine-grained marine sediments. In: Stow, D.A. and D.J.W. Piper (eds.), *Fine-Grained Sediments: Deep-Water Processes and Facies*. Blackwell Scientific Publications, Palo Alto, CA, 659 p.
- Mehta, A.J., 1973. Depositional behavior of cohesive sediment. Ph.D. Dissertation, University of Florida, Gainesville, FL, 275 p.
- Mehta, A.J. (ed.), 1986. *Estuarine Cohesive Sediment Dynamics. Lecture Notes on Coastal and Estuarine Studies 14*. Springer-Verlag, New York, 473 p.
- Migniot, G., 1968. A study of the physical properties of various forms of very fine sediment and their behavior under hydrodynamic action. *La Houille Blanche*, v. 7, p. 591-620 (in French).
- Mimura, N., 1989. Recent Japanese studies on cohesive sediment transport. *Journal of Coastal Research. Special Issue No. 5*.
- Mitchell, J.K., 1976. *Fundamentals of Soil Behavior*. Wiley, New York, 422 p.
- Monin, A.S., and R.V. Ozmidov, 1985. *Turbulence in the Ocean*. D. Reidel, Boston, MA, 247 p.
- Nychas, S.G., H.C. Hershey, and R.S. Brodkey, 1973. A visual study of turbulent shear flow. *Journal of Fluid Mechanics*, v. 61, p. 513-540.
- Offen, G.R., and S.J. Kline, 1974. Combined dye-streak and hydrogen-bubble visual observation of a turbulent boundary layer. *Journal of Fluid Mechanics*, v. 62, p. 223-239.
- Offen, G.R., and S.J. Kline, 1975. A proposed model of bursting process in turbulent boundary layer. *Journal of Fluid Mechanics*, v. 70, p. 209-228.
- Ohtsubo, K., and K. Muraoka, 1986. Resuspension of cohesive sediments by currents. In: Wang, S.Y., H.W. Shen, and L.R. Ding (eds.), *River Sedimentation, v. III, Proceedings of the Third International Symposium on River Sedimentation*, p. 1680-1689.
- Owen, M.W., 1977. Problems in the modeling of transport, erosion, and disposition of cohesive sediment. In: Goldbert, E.D. et al. (eds.), *The Sea*, v. 6, Wiley-Interscience, New York, 1048 p.
- Partheniades, E., 1962. A study of erosion and deposition of cohesive soils in salt water. Ph.D. dissertation, University of California, Berkeley, CA, 181 p.
- Partheniades, E., 1965. Erosion and deposition of cohesive soils. *Journal of the Hydraulic Division, American Society of Civil Engineers*, v. 91, no. HY1, Proceedings Paper 4202, p. 105-139.
- Partheniades, E., 1977. Unified view of wash load and red material load. *Journal of the Hydraulic Division, American Society of Civil Engineers*, v. 103, no. HY9, Proceedings Paper 13215, p. 1037-1057.
- Partheniades, E., 1986. A fundamental framework for cohesive sediment dynamics. In: Mehta, A.J. (ed.), *Estuarine Cohesive Sediment Dynamics. Lecture Notes on Coastal and Estuarine Studies 14*. Springer-Verlag, New York, 473 p.
- Richardson, M.D., and D.K. Young, 1980. Geoaoustic models and bioturbation. *Marine Geology*, v. 38, p. 205-218.
- Schlichting, H., 1960. *Boundary Layer Theory*, 4th ed. McGraw-Hill, New York, 647 p.
- Shen, Y.P., 1986. Second order closure modeling of turbulent flow and sediment dispersion in coastal and estuarine waters. In: Wang, S.Y., H.W. Shen, and L.Z. Ding (eds.), *River Sedimentation, v. III, Proceedings of the Third International Symposium on River Sedimentation*, p. 1383-1396.
- Smith, J.D., 1977. Modelling of Sediment Transport on Continental Shelves. In: Goldbert, E.D. et al. (eds.), *The Sea*, v. 6, Wiley-Interscience, New York, 1048 p.
- Swift, D.J.P., D.B. Duane, and O.H. Pilkey (eds.), 1972. *Shelf Sediment Transport: Process and Pattern*. Dowden, Hutchinson & Ross, Stroudsburg, PA, 656 p.
- Teleki, P.G., 1972. Wave boundary layers and their relation to sediment transport. In: Swift, D.J.P., D.B. Duane, and O.H. Pilkey (eds.), *Shelf Sediment Transport: Process and Pattern*. Dowden, Hutchinson & Ross, Stroudsburg, PA, 656 p.
- Townsend, A.A., 1976. *The Structure of Turbulent Shear Flow*. Cambridge University Press, Cambridge, 429 p.
- Weggel, J.R., 1972. An introduction to oceanic water motions and their relation to sediment transport. In: Swift D.J.P., D.B. Duane, and O.H. Pilkey (eds.), *Shelf Sediment Transport: Process and Pattern*. Dowden, Hutchinson & Ross, Stroudsburg, PA, 656 p.
- Yalin, M.S., 1977. *Mechanics of Sediment Transport*. Pergamon Press, New York, 298 p.

✓

By	
Date	
Received by	
Dist	Assigned to
A-1	20

